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APPLICANT(s):	Sonti, et al.	CONF. NO.:	3267
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TITLE: METHOD AND APPARATUS FOR STRENGTHENING OF POWDER METAL GEARS BY AUSFORMING

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Declaration Under 37 C.F.R. 1.132

We, Dr. Nagesh Sonti, Dr. Suren B. Rao, and Prof. Maurice F. Amateau, being as listed inventors in the subject patent application do hereby state that:

I, Nagesh Sonti, have over nineteen years of experience in the design and production of gears. In addition, I have over thirty three years of experience in thermal-mechanical processing of steels, including heat treatment, joining, machining and finishing of steel components. I am presently a Research Engineer at the Applied Research Lab at Pennsylvania State University. I have a Ph.D. in Engineering Science and Mechanics from Pennsylvania State University, a Masters degree in welding engineering from Ohio State University and a Bachelors degree in mechanical engineering from the University of Madras, India, and

I, Suren B. Rao, have over twenty four years of experience in the design and production of gears, and over thirty seven years of experience in the machine tool industry. I am

presently a Senior Scientist at the Applied Research Lab at Pennsylvania State University. I have a Ph.D. in mechanical engineering from the University of Wisconsin-Madison, a masters degree in Mechanical Engineering from McMaster University, Canada and a Bachelors in engineering from Bangalore University, India, and

I, Maurice F. Amateau, have over thirty years of experience in the design and production of gears. In addition, I have over forty three years of experience in thermal-mechanical processing of steels, including heat treatment and finishing of steel components, as well as over fifty years of experience in the metallurgical arts. I am a retired Professor and Chief Scientist at the Applied Research Lab at Pennsylvania State University. I have a Ph.D. in metallurgy and a Masters degree in metallurgical engineering from Case Western University and a Bachelors degree in metallurgical engineering from Ohio State University.

We are familiar with the apparatus and method for precision gear finishing by controlled deformation of U.S. Patent No. 5,451,275 (the reference Amateau et al., hereinafter "Amateau"), the full form roll finishing technique of U.S. Patent No. 6,779,270 (the reference Sonti et al., hereinafter "Sonti") and the powder metal gear wheels rolled from powder metal blanks and the method of manufacturing the same of U.S. Patent No. 5,711,187 (the reference Cole et al., hereinafter "Cole"). To the best of our knowledge and belief, the apparatus and methods of Cole are not equivalent with the manufacturing methods of Amateau and Sonti so as not to be a mere substitution of one technique for another or the mere application of a known technique to a piece of prior art ready for improvement.

1. Amateau provides an apparatus and method for finishing wrought and/or forged steel gear wheels in which a previously carburized and hardened gear, hardened to over 60 HRC, is finished to its final shape by thermal-mechanical means by inducing controlled plastic deformation in the metastable austenitic condition via gear rolling. The method described in Amateau is applicable to gear tooth surfaces that contain high carbon content of over 0.6% by weight, such high carbon in the surface layers being necessary to result in high surface and case hardness that is required in gear teeth to transmit power.

2. Sonti describes a full form roll finishing technique that results in plastic deformation and moving or smearing of tooth surface material in the root/fillet regions as well of gear wheels made of wrought and/or forged gears, thereby extending the beneficial features of conventional gear roll finishing as well as the method described in Amateau to the entire full form of the gear teeth including the active contacting surfaces as well as the trochoidal root/fillet regions. No final finishing steps, such as grinding are needed to obtain the final shape of the gear.

3. For wrought and/or forged gear wheels, thermal-mechanical method of ausform gear roll finishing described in Amateau and Sonti results in substantial material flow up and down the tooth surfaces and in the axial direction due to combined rolling and sliding action on the tooth surfaces, so that the outer most surface layers are not removed during ausform finishing operation, but instead are moved or smeared laterally on the tooth surface layers. No

final finishing steps, such as grinding are needed to obtain the final shape of the gear.

4. The methods and apparatus described in Amateau and Sonti are applicable to both low carbon gear steels that are then carburized/hardened to increase the amount of carbon in the surface layers, as well as through hardening type gear steels that are produced with inherently high carbon during steel making. For gear wheels made of wrought and/or forged steels, the rolling dies for thermal-mechanical finishing are designed for combined rolling and sliding action on the tooth surface layers, wherein the material flow is laterally oriented in the tangential direction up and down the gear teeth as well as in the axial direction, but not in the radial direction as no radial compaction of the material is possible.

5. The method described in US Patent Cole, applies to a powder metal gear wheel that has been produced from a pressed and sintered powder metal blank that results in surface densification of tooth surface layers. The Cole patent describes a prefinishing technique of gear rolling, that is performed prior to heat treatment and hardening, using either a single-die or a double-die rolling apparatus, and is applicable for sintered low alloy steel compositions similar to SAE 4100, SAE 4600, and SAE 8600 grades. The method described in Cole is applicable only to low carbon low alloy sintered steel compositions in the soft machinable condition with hardness substantially less than HRC 24, particularly with carbon content of 0.2% or less because the Cole patent is a prefinishing operation that is performed prior to heat treatment and hardening. A

final finishing operation is needed in Cole to obtain the final shape of the gear teeth.

6. Cole is not equivalent with Amateau or Sonti

a. Amateau and Sonti provide a finished gear that does not require any post forming operations for shaping the gear teeth.

b. Cole provides a pre-finishing technique for shaping gear teeth. Further processing of the gears in Cole, either in the as-sintered condition or after surface densification as described in the Cole patent, is required after the initial forming of the teeth to achieve the specified surface hardness, hardness gradient and core strength necessary for high load bearing capability.

The gears of Cole have to be case hardened by carburizing and hardening operations. Case hardening heat treatment inherently results in substantial distortion of gear teeth, and therefore substantial loss results in accuracy and surface finish that was previously induced by prefinishing using the method of Cole.

Because of the substantial distortion of the gear teeth from the hardening operations, the sintered and densified powder metal gears, as produced by method described in Cole require subsequent hard finishing by grinding, skiving, burnishing, or honing operations to achieve the required level of accuracy and performance, processes that result in removal of about 150 microns of the densified surface region of gear

teeth. Removal of the surface layers of about 150 microns thereby lowers the load bearing capacity because part of the surface region with densified surface layers, achieved using method as described in Cole patent followed by heat treatment, is removed thereby negating Cole's original densification intent.

The powder metal gear wheels produced by the method described in Cole and then case hardened cannot be used as power transmission gearing that require high level of accuracy and surface finish for adequate performance equivalent to current wrought steel gear wheels, unless some post hardening finishing operation such as grinding is applied.

c. Powder metal sintered and case hardened steel gear wheels inherently contain substantial amount of pores with effective density in the range of 90-95% of theoretically fully dense steel alloy. These pores have to be compacted to densify the surface of the gear wheel to alleviate cracking and/or breaking of the gear teeth. The material flow characteristics of the wrought and/or forged steels of Amateau and Sonti are such that only lateral flow occurs up and down the tooth surface and no radial compaction is possible.

d. Surface densification of powder metal gears as described in Cole results in a gradient in densification. That is the outer most layer is densified to nearly full density, and the subsequent layers are densified to lesser and lesser amounts. After about 1mm, the core density of the perform gear is reached. Therefore, in order to induce sufficient

surface densification to effect improved properties, substantial gear tooth size reductions must be induced by the surface densification operation. Typical tooth size reductions are as much as 0.010". Rather than the geometry of the tooling, the geometry of preform gear has more influence on the process. In contrast, for the methods described in Amateau and Sonti, typical tooth size reduction is about 0.003" or less. Furthermore, as described in Sonti, the amount of material flow may vary from a maximum at the tooth flanks to zero at the bottom of the root fillet. This difference of tooth size reduction between powder metal gears and wrought/forged steel gears is critical in the design of the tooling. Tooling geometry shape must be optimally designed for proper conjugacy to induce precise amount of stock flow at various locations of the gear teeth.

The rolling dies used for finishing of sintered and case hardened powder metal gear wheels are required to be designed not to move or smear material laterally up and down the teeth, but instead are designed specifically to cause densification of surface layers involving substantial radial compaction of the material in the tooth surface layers, thus resulting in the collapsing of the pores and densification of the gear surface. This is directly contrary to the rolling dies used for finishing the wrought and/or forged gear wheels of Amateau and Sonti.

e. Gear rolling of soft sintered gear tooth surfaces as described in Cole produces densification of tooth

surface layers. Plastic deformation induced by the method of Cole is essentially radial compaction. Such radial compaction is not possible when forming wrought and/or forged gear wheels of Amateau and Sonti.

The formation of gear wheels from wrought or forged steel involves plastic deformation of gear tooth surface layers, resulting in smearing of material over the tooth surfaces. Plastic deformation of wrought or forged material involves permanent plastic flow, but with zero volume change. Plastic deformation depends on the flow stress (eg. yield stress in uniaxial loading) of the material as well as formability (ability to deform without failure). Flow stress is influenced by material composition and related microstructural features, as well as strain, strain rate and temperature. In contrast, surface densification of conventional powder metal gears as described in Cole involves substantial volume change due to collapsing of pores. Compressibility of the material plays the most significant role, which is influenced by porosity amount and distribution, as well as material composition, prior strain and/or heat treatment history. In the case of Cole, the primary factors are therefore porosity and steel composition/phase.

Constitutive relations or plastic flow rules that are applicable for constant volume plastic deformation of wrought or forged steels are either Tresca's maximum shear stress criteria for yield, or Von Mises minimum distortion energy criteria for yield. These are not

applicable for surface densification of soft powder metal steel gears via compaction, as these materials are compressible due to the inherent pores and therefore volume is not constant.

For plastic deformation of wrought or forged material below the steel recrystallization temperature (defined as cold forming), strain rate effects are generally not significant, whereas strain effects (i.e. strain or work hardening) are quite significant. That is, after some plastic flow, additional flow requires increasingly higher stresses. On the otherhand, surface densification of powder metal gears as described in '187, is applicable to powder metal compositions with low carbon content of 0.2% or less, and is carried out at room temperature. In Cole, the gear in the as pressed and sintered condition prior to surface densification is soft, consisting entirely of ferritic/pearlitic phase, with apparent hardness of 180-200 BHN. As surface densification described in Cole only involves compaction of soft surface layers, work hardening effects are not significant.

f. Cole describes only a method required to densify the teeth of gear wheels produced using soft low carbon containing powder metal sintered steel containing substantial amount of porosity. Material flow properties and work hardening characteristics of high carbon metastable austenitic steel, as in Amateau and Sonti, are inherently and substantially different from soft low carbon containing powder metal sintered ferritic/pearlitic steel, and therefore the method

described in Cole which applies to only soft ferritic/pearlitic powder metal sintered steel is inadequate.

g. Performance of gear wheels in surface durability fatigue tests have shown that powder metal gear wheels produced by the method described in Cole do not equal surface durability performance of the wrought steel gears as produced by Amateau and Sonti.

h. Densification of the gear surface in Cole results in a core density which is lower than that in the densified regions or surfaces of the gear teeth, which is typically at around 90% of full theoretical density of wrought steel. This results in a tooth with comparatively lower bending fatigue endurance than its machined wrought steel counterpart.

7. In contrast to the method described in Cole, the method described in the current application results in finished powder metal gear wheels with high hardness, strength, accuracy and surface finish that do not require any further post hardening operations. It is to be noted that performance of gear wheels in surface durability fatigue tests have shown that powder metal gear wheels produced by the method described in the present application have been demonstrated to not only equal but surpass the surface durability performance of current wrought steel gears.

8. Mechanical properties (modulus of elasticity, yield strength, fatigue strength, etc.) for soft powder metal steels in pearlitic/ferritic condition are primarily a function of material composition and porosity in both amount

and distribution. Strain and strain rate effects are negligible. Contact pressure and width, which a function of the modulus and yield strength, are therefore affected primarily by the degree of porosity. In contrast, mechanical properties for hardened powder metal steels are not only a function of material composition and porosity, but also the metallurgical phase (tempered martensite or metastable austenite), and the respective work hardening characteristics. Contact pressure and width are therefore affected by the work hardening characteristics of metastable austenite, and the underlying mixture of metastable austenite and hardened tempered martensite, as well as by the degree of porosity.

And, further, that all statements made herein based on our knowledge are true and that all statements made on information and belief are believed to be true, and that we are aware that willful false statements and the like are punishable by fine or imprisonment, or both (18 U.S.C. 1001), and may jeopardize the validity of this application, document, or patent issuing therefrom.

______________________ Dated: Sept 6, 2007

Dr. Nagesh Sonti

______________________ Dated: Sept 6, 2007

Dr. Suren B. Rao

______________________ Dated: Sept 5, 2007

Prof. Maurice F. Amateau